

## Research Article

# Suitability of Water Harvesting in the Upper Blue Nile Basin, Ethiopia: A First Step towards a Mesoscale Hydrological Modeling Framework

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Extreme rainfall variability has been one of the major factors to famine and environmental degradation in Ethiopia. The potential for water harvesting in the Upper Blue Nile Basin was assessed using two GIS-based Multicriteria Evaluation methods: (1) a Boolean approach to locate suitable areas for in situ and ex situ systems and (2) a weighted overlay analysis to classify suitable areas into different water harvesting suitability levels. The sensitivity of the results was analyzed to the influence given to different constraining factors. A large part of the basin was suitable for water harvesting: the Boolean analysis showed that 36% of the basin was suitable for in situ and ex situ systems, while the weighted overlay analysis showed that 6–24% of the basin was highly suitable. Rainfall has the highest influence on suitability for water harvesting. Implementing water harvesting in nonagricultural land use types may further increase the benefit. Assessing water harvesting suitability at the larger catchment scale lays the foundation for modeling of water harvesting at mesoscale, which enables analysis of the potential and implications of upscaling of water harvesting practices for building resilience against climatic shocks. A complete water harvesting suitability study requires socioeconomic analysis and stakeholder consultation.

## 1. Introduction

Rainfed agriculture will remain the dominant source of staple food production and the basis for livelihoods of the majority of the rural poor in Ethiopia [1, 2]. The major challenge for agriculture in Ethiopia is the extreme variability in rainfall, characterized by high intensity storms, and high frequency of dry spells and droughts [3–6]. Drought has been responsible for the partial to complete crop failure in the semiarid and dry subhumid parts of the country. Flooding brought on by intense storms has washed away the fertile top soil, river banks, and beds of the river course, displacing hundreds of thousands of people settling around the floodplains. Climate change projections have shown that these climatic shocks are likely to become even worse in the coming decades [7]. Extended dry periods in combination with more frequent storm floods, a rugged topography and high population

pressure has caused large soil erosion and land degradation in the highlands of Ethiopia [8–10]. These degradation processes have been aggravated by intensive farming and livestock grazing. The biodiversity and environmental health of aquatic ecosystems are seriously threatened by the land degradation on agricultural lands [11]. Such degradation is likely to affect the local hydrology, resulting in reduction of evapotranspiration fluxes during the rainy season. This in turn affects the feedback of moisture to the atmosphere, which reduces the recycling of moisture and thereby may reduce the rainfall further inland [12–14].

Studies have shown that water harvesting systems, that is, methods for concentrating, collecting, and storing rainfall water in different mediums for domestic or agricultural uses [15–18], can turn these inherent challenges of large rainfall variability into opportunities to build resilience in rainfed agriculture. These technologies are classified into two main

categories: ex situ and in situ water harvesting systems. Ex situ systems have water harvesting capture areas external to the point of water storage. Examples of ex situ water harvesting system include farm dams, open tanks, cisterns, ponds, runoff farming systems, and small reservoirs [19–22]. In situ water harvesting systems, on the other hand, trap and retain the water from rainfall in the root zone of the soil where it falls [23–25]. In situ water harvesting systems include pitting, Fanya juu, stone lines/bunds, and conservation tillage [20, 22, 25, 26]. These practices can help bridge dry spells and drought by storing part of the rainfall, which is otherwise lost (from the perspective of the local farmer) as evaporation, interception, and surface runoff and which can amount to 70–80% of the rainfall in semiarid savannah farming systems [27]. Large scale implementation of water harvesting systems represents an essential step toward a resilient, productive farming system, which can produce more crop per drop of water, while at the same time having the capacity to deal with stress and shock induced by extreme water variability [28, 29]. For example, a small pond ( $\sim 1000 \text{ m}^3$ ) filled with runoff water can provide about half the total crop water requirement of a half a hectare cultivated field, which can translate a very low crop yield into a modest success [30]. On-farm research in Burkina Faso and Kenya showed that 60–80 mm applications of supplemental irrigation (corresponding to 2–3 supplementary rainfall events in rainy seasons that generally have only  $\sim 20$  or so larger rainfall events) at critical stages of a crop growth cycle, combined with nutrient application, improved rainfed yield levels from less than 1 ton/ha to 1.5–2.5 ton/ha for a sorghum and maize grain [21, 31]. In addition, by storing excess runoff a chain of water harvesting structures can flatten the hydrograph in streams, which consequently reduces flooding. They can also increase the infiltration of water into the root zone and further percolation into the groundwater [23, 32, 33], which is important to provide a sustained stream flow downstream [34].

Blue water and green water availability at the larger catchment and river basin scale is a result of rainfall partitioning at the soil surface and root zone [35, 36]. Blue water resource is the liquid water in rivers, lakes, and aquifers, while the green water is the naturally infiltrated rain attached to soil particles and accessible to roots [37]. The green water is divided further into green water storage (e.g., soil moisture) and green water flow (e.g., evapotranspiration). Water harvesting systems will play a major role in this blue-green water partitioning process. Collection of local runoffs in these systems will increase green water storage upstream and may reduce the blue water flows, which could support ecosystem services downstream [1]. However, these practices can possibly enhance the green water flows at regional scale by influencing rainfall levels through moisture feedback and, thereby, the availability of blue water resources [38]. Furthermore, in situ water harvesting practices such as subsoiling, manual pitting, ripping, and zero tillage systems improve soil fertility and contribute to immediate productivity benefits and long-term resilience building [34].

Given the following four considerations: (i) the predominance of rainfed agriculture in semiarid and dry subhumid

tropical regions of the world, (ii) the pressing need to increase agricultural productivity to meet growing food demands, (iii) the growing risks of increased rainfall variability due to climate change in already water limited agricultural systems, and (iv) the opportunity of adopting water harvesting systems as a strategy to build resilience in local farming systems, the question is what potential water harvesting systems have to enhance water related resilience in rainfed farming systems located in regions prone to periods of water scarcity? The first step towards an answer is to analyze the suitability of water harvesting systems in different agroecological contexts. Surprisingly, there are relatively few spatial analyses of water harvesting suitability [30, 39–42]. Despite decades of evidence of the potential for water harvesting systems to enhance farm productivity and reduce water related risks, there is a knowledge gap in methods for analyzing the suitability of water harvesting systems at the catchment scale. This gap affects the quality and relevance of water resource planning, assessments, and spatial hydrological modeling.

Such suitability analyses should be based on a technical and agroecological feasibility studies to identify the potential for and maximize the benefits from these interventions. This paper develops and presents a suitability analysis for water harvesting in the Upper Blue Nile Basin in Ethiopia using biophysical data. Suitable areas for water harvesting systems implementation are in this paper defined as areas which are appropriate for (i) runoff generation, (ii) water storage, and (iii) agricultural production. Mati et al. [40] have given a general continent-wide overview on water harvesting suitability in Africa and selected countries and labeled areas as either suitable or unsuitable for rainwater harvesting. This study, besides classifying areas as either suitable or unsuitable for in situ and ex situ water harvesting systems in the Upper Blue Nile Basin, also classifies areas into different levels of suitability for water harvesting. Building upon the type of classifications presented by Mati et al. [40], this study used data of higher spatial resolutions to fine-tune the classifications of areas suitable for water harvesting. Moreover, this paper assesses the influence of different biophysical constraints on implementing water harvesting systems. It also tries to identify priority areas (e.g., mesoscale catchments,  $1 \text{ km}^2$ – $10,000 \text{ km}^2$ , Uhlenbrook et al. [43]) that are highly suitable for water harvesting where large scale adoption in the future of water consuming systems upstream may generate implications downstream for social and ecological functions and services due to a reduction in available water.

## 2. Method and Material

**2.1. The Study Area.** The Upper Blue Nile Basin of Ethiopia occupies an area of  $199,812 \text{ km}^2$  and is located within eastern and central Ethiopia [44]. The basin contains a mixed topography of high mountains, rolling ridges, flat grassland areas, and meandering streams that can create magnificent waterfalls where they plunge over the escarpment to lowland areas. Lake Tana is the largest lake in the basin and is located in the north-eastern part of the basin and is the source of the Abay (Blue Nile) River. The climate of the basin is primarily

influenced by altitude and the proximity to the equatorial monsoonal systems. The year is divided into three seasons: a rainy season (Kiremt) which occurs around July and August, a dry season (Bega) from November to January, and “small rains” season (Belg) that may occur around April [3, 5, 45]. Rainfall variability is an inherent phenomenon in the Upper Blue Nile Basin [46, 47].

Nationwide statistics indicated that 84% of the Ethiopian's livelihood depends on agriculture [48]. Agriculture in Ethiopia accounts for 47% of GDP, 90% of all exports, and 85% of employment [49]. The government of Ethiopia follows an agricultural based industrialization economic policy to reduce poverty and also generate economic development. One of the strategies to achieve this objective is by investing in water resources development [50]. Water harvesting investments have been among the main pillars in the National Food Security Strategy to bridge droughts and dry spells, which are intrinsic features of rainfall variability. However, the water harvesting implementation with the blanket recommendation has passed through severe challenges which are attributed to lack of adequate study, design, and implementation [51].

**2.2. Spatial Datasets.** The annual rainfall dataset used in this study was obtained from the WorldClim Global Climate Data [52] (Figure 1(a)). This data layer was generated through interpolation of average monthly climate data from weather stations on a 30-arc-second resolution grid [53]. The merits of this dataset over previous global climate datasets (e.g., [54–56]) are that it has a higher spatial resolution (400 times greater or more), is based on a greater number of weather station records, and uses improved elevation data. It also uses more information about spatial patterns of uncertainty [53]. A Digital Elevation Model (DEM) (90 m resolution) from the CGIAR consortium for spatial information [57] was used to create a slope map (Figure 1(b)). The land cover map used in this study was obtained from the Ethiopian Ministry of Water Resources [58] (Figure 1(c)). The land cover of the basin essentially follows the divide between highland and lowland; almost the entire highland area is under farmland and in contrast the lowlands are still largely virgin [44]. Areas which consist of predominantly cultivated land were classified as “dominantly cultivated” and those with lower land use for farmland as “moderately cultivated.” Other major land use types in the basin include bamboo, woodland, bushland, shrub, grassland, wetland, rockland, and urban areas. The land use coverage analysis showed that more than 50% of the basin is cultivated land, 32% woodland, and 6% grassland and the remaining 12% is covered by other land use types (Figure 1(c)). The soil map of the study area is obtained from the Ethiopian Ministry of Water Resources [58] (Figure 1(d)). In the eastern part of the basin, Leptosols are most common, which are shallow soils with limited profile development that are prone to drought, water logging, and high runoff yields [44, 59, 60]. In the western part of the basin there are a variety of soil types such as Nitosols and Alisols and some less productive soil types [44]. Nitosols have high inherent fertility and are among the most productive agricultural

soils within the basin, while Alisols are highly acidic, poorly drained soils prone to toxicity and water erosion [44, 59, 60]. Minor soils such as Arenosols, Regosols, and Phaeozems cover about 1% of the basin. The soil and land use map has a scale of 1 : 250,000 [44], which is finer than the data used by other studies (e.g., [40]) which is 1 : 5,000,000.

**2.3. Data Processing.** The global datasets are clipped to include only the study area extent and are subsequently projected into the Ethiopian projected coordinate system (UTM, other GCS, Adindan UTM zone 37N.prj). Shape files were converted into raster layers as the overlay analysis works in a grid data format. Moreover, the slope raster was created from the DEM in percentage of slope using the spatial analyst tool. A flow chart (Figure 2) presents the procedures used to process the data sets. Multicriteria Evaluation (MCE) in ArcGIS were used to study the suitability of the basin for water harvesting using two different approaches: an AND Boolean operation and a weighted overlay analysis.

**2.3.1. AND Boolean Analysis.** The AND Boolean operation identified the locations which fulfill all suitability criteria included in the decision set. Such a procedure is essentially risk-averse and selects locations based on the most cautious strategy possible; a location succeeds in being selected only if its worst quality passes the test [61]. On the other hand, if a logical OR (union) had been used, the opposite applies; a location would have been included in the decision set even if only a single criterion passes the test. This latter approach is thus a gamble, involving substantial risk [61]. Hence, the AND Boolean operation can provide the potential water harvesting locations under a conservative approach. It is furthermore assumed that for water harvesting one criterion cannot compensate for another. This methodology was applied to map suitable locations for in situ and ex situ water harvesting systems.

In situ systems can be implemented in any hydroclimatic and physical conditions as they can serve as both soil and water conservation practices. However, in this analysis only cultivated land areas that receive an average annual rainfall of 200–1200 mm are considered. Experience suggests that water harvesting systems in tropical regions are relevant within this rainfall range [40]. This is because areas with rainfall less than 200 mm are arid regions with low population densities and a high risk of production failure with a predominance of pastoral or agropastoral communities and that water availability is not a constraint to food production in areas with a rainfall amount of more than 1200 mm [40]. The minimum rainfall suitability criterion range considers the suggestion by Critchley and Siegert [62] that the design of water harvesting systems has to consider the water requirement of the crop intended to be grown, which in the study area ranges from 300–500 mm (for beans) to 450–700 mm (for Soybean). From interviews with the farmers and expert experience in the region, we have learnt that in areas where the rainfall is very high (>1200 mm), farmers are more interested in water drainage than in situ harvesting as it affects their agricultural activity due to water logging. Although these areas are not

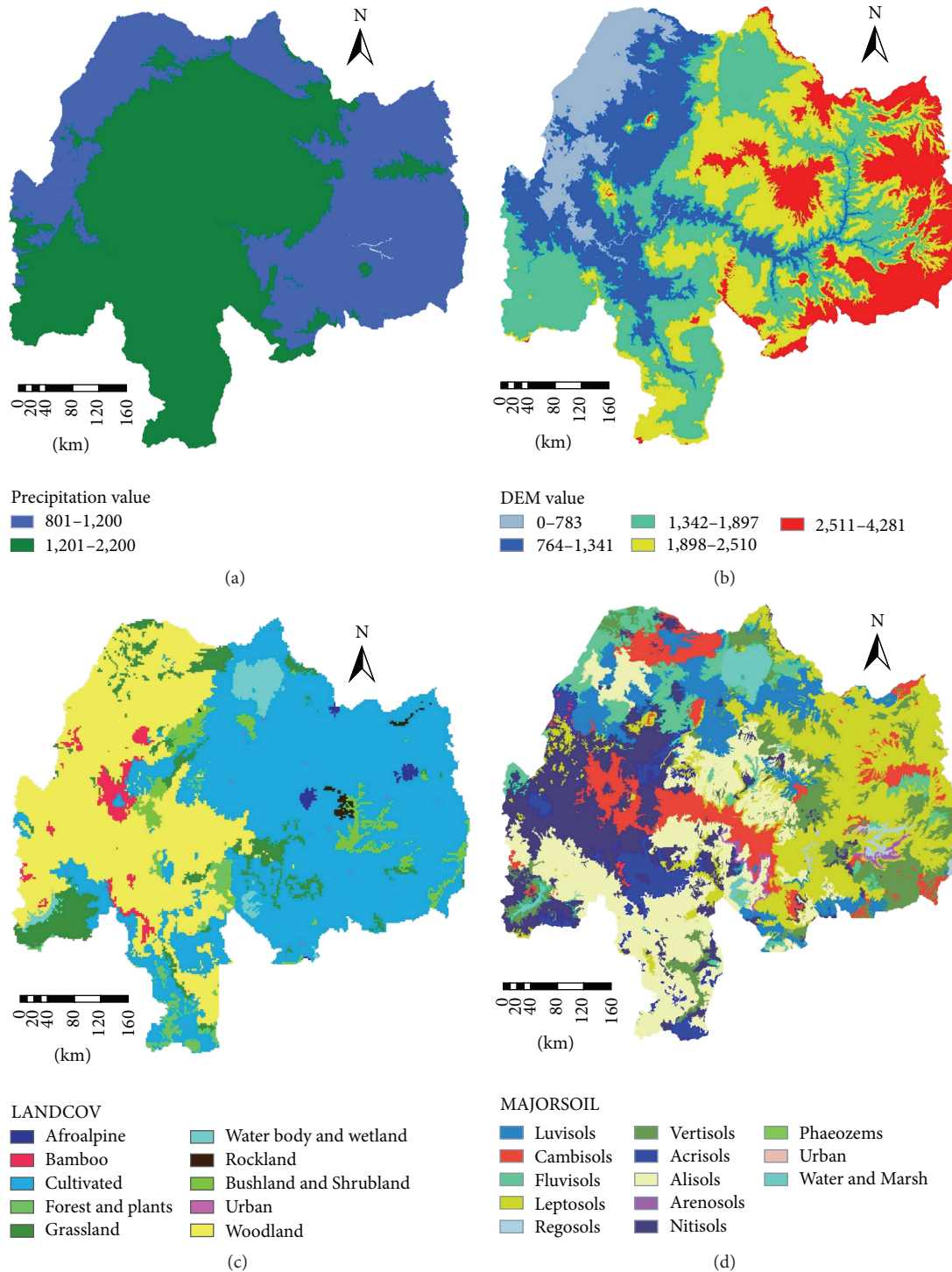


FIGURE 1: Spatial datasets used for the water harvesting suitability study of the Upper Blue Nile Basin: (a) annual rainfall (mm), (b) DEM (meters above sea level), (c) land cover map, and (d) soil types.

necessarily unsuitable for water harvesting, it seems clear that the incentive for farmers to invest in water harvesting declines sharply when rainfall reaches levels above 1200 mm. Slope is not considered as a constraint factor for in situ systems as it can be altered by bunding and terracing [40].

For ex situ water harvesting systems, areas which receive >200 mm of annual rainfall, cultivated land cover types, and a slope <8% were considered suitable [40]. Steep slopes are associated with larger risks of soil erosion and pose larger difficulties in the design of storage systems and hence



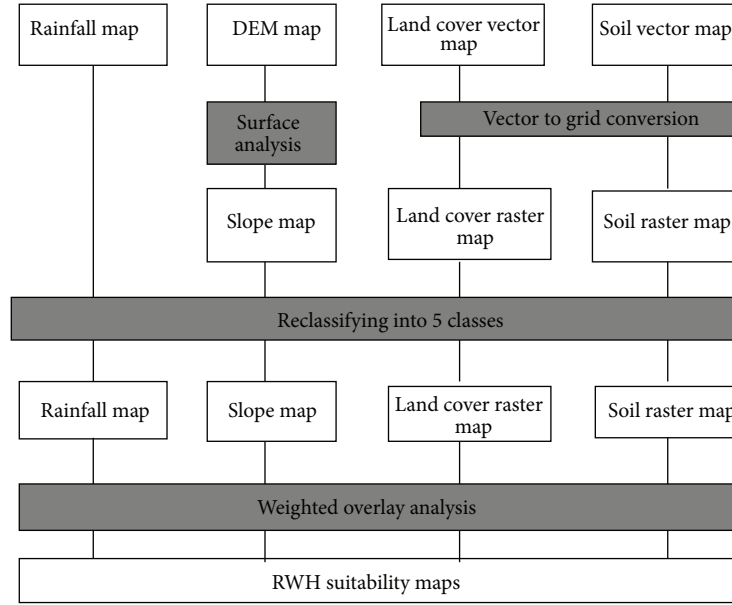


FIGURE 2: Flow chart of the data preparation and weighted overlay analysis for identifying the suitability of water harvesting systems.

considered as less convenient for ex situ water harvesting activities [40, 62].

Even if most of the cultivated area consists of Leptosols, which are less suitable for agriculture, soil type is not considered as a constraint factor in the Boolean MCE analysis. In the Upper Blue Nile Basin, agriculture is already practiced in less productive and degraded soils. One could argue that only the best soil types would motivate investments in water harvesting systems as a way to ensure the best possible economic outcome from the investment. This would suggest including soil quality as a criterion. In the Ethiopian setting we suggest that this argument is not applicable, as most farmers already cultivate degraded soils, and that farmers are entirely dependent on this agriculture for their livelihoods. Instead we consider water harvesting systems as a tool to upgrade the existing rainfed agricultural system. The criteria used for the Boolean MCE analysis are summarized in Table 1.

**2.3.2. Weighted Overlay Analysis.** A weighted overlay analysis was performed to examine to what extent the different pixels (areas) are suitable for water harvesting practices. This analysis was also important for estimating the extent of the suitable area (maximum and minimum range) for water harvesting in the Upper Blue Nile Basin by applying different percentage influence to the constraint factors. Besides, by progressively assigning different percentage influence to the constraint factors, the sensitivity of the results of the suitability study to the constraint factors was investigated. This approach is used to identify the most important constraint factors in determining suitable areas for water harvesting in the region. Understanding the sensitivity of the results to the different constraint factors would allow further studies to concentrate effort on the factors that will have the largest impact.

TABLE 1: Criteria for suitability of in situ and ex situ water harvesting systems.

Factors	In situ systems	Ex situ systems
Slope	N.A.	<8%
Rainfall	200–1200 mm	>200 mm
Land use	Cultivated areas	Cultivated areas

The weighted overlay analysis is neither risk-taking nor risk-averse. Rather it analyses tradeoffs between the constraint factors. In this analysis a very poor quality can be compensated for by having a number of very favorable qualities in the general assessment of the suitability of an area. This can be achieved by applying a weight for each factor considered in the analysis and summing the results to yield a suitability map according to the equation:  $S = \sum w_i x_i$ , where  $S$  is the final suitability score,  $w_i$  is weight of factor  $i$ , and  $x_i$  is suitability score of factor  $i$ . A suitability score of 1 to 5 is assigned for each factor as shown in Table 2, where 5 represents the highest suitability and 1 the lowest suitability. This assignment is used to reclassify values into identical impact levels and to perform arithmetic operations with other rasters.

The classification for rainfall followed the recommendation by Mati et al. [40] and Kahinda et al. [39]. According to Mati et al. [40] there is no need to invest in water harvesting systems in areas with annual rainfall below 200 mm and above 1200 mm. Areas receiving an annual rainfall of 400–1200 mm are considered optimal for obtaining extra benefits from water harvesting. The suitability classes for slope recommended by Mati et al. [40] and Mbilinyi et al. [41] were used. Water harvesting is less suitable in areas where the slope is more than 8%. According to Critchley and Siegert [62] water harvesting is not recommended in steep slopes due to uneven

TABLE 2: Suitability classes of different constraint factors used to identify suitable areas for water harvesting schemes using MCE weighted overlay technique.

Suitability score ( $x_i$ )	1	2	3	4	5
Rainfall (mm)	<200	>1200	200–400	800–1200	400–800
Slope	>20%	12–20%	8–12%	2–8%	<2%
Land cover	Bushland, forest, woodland, grassland swamp, Shrubland	N.A.	N.A.	Plantations irrigated land	Cultivated land
Soil	N.A.	Leptosols	Arenosols, Regosols	Vertisols Acrisols, Alisols	Luvisols, Cambisols Fluvisols, Nitisols

TABLE 3: Relative percentage influence factors ( $w_i$ ) used in the weighted overlay analysis.

Parameter	Percent influence				
	Condition 1	Condition 2	Condition 3	Condition 4	Condition 5
Rainfall	25	30	35	25	35
Slope	25	30	25	35	30
Land cover	25	20	20	20	20
Soil	25	20	20	20	15

distribution of runoff and large quantities of earth work required which is uneconomical. As the focus of this study is water harvesting for agriculture, a high suitability score was given to cultivated land use types, while woodland and grassland were assigned a lower suitability score. The texture and mineral composition of a soil type affect its suitability for agriculture and water harvesting. Sandy-clay textured soils (i.e., soils with a clay content of 15–35%) are most suitable as a runoff and run-on area for water harvesting schemes [39, 41]. The soil suitability score for water harvesting and agricultural production was classified based on the FAO's soil description [59, 60].

Five categories of percentage influence ( $w_i$ ) were applied in the sensitivity analysis of each constraining factor (Table 3). This is to explore the water harvesting potential for different conditions. For condition 1, an equal percentage influence for all the factors was employed, and for other conditions a higher influence was assigned for the rainfall and slope. Mati et al. [40] and Mbilinyi et al. [41] argued that rainfall and slope are the most influencing factors in water harvesting schemes. Conditions 3 and 4 were meant to test the sensitivity of the suitability classification results to rainfall and slope by assigning a higher weight consecutively (i.e., 35% for rainfall and 25% for slope in condition 3 and vice versa in condition 4). In condition 5, distributed percentage influence was applied for each factor based on the lessons learned from the successive results of other conditions. In this last condition, soil is given lower influence in the analysis following the same reasoning as discussed in Section 2.3.1.

**2.4. Validation of the Results.** Even though water harvesting has been practiced in Ethiopia for several years, extensive spatial documentation on the location of these interventions is not available in Ethiopia. Therefore, it was difficult to perform a comprehensive validation of the findings. However, we

extracted the coordinates of existing water harvesting practices from reports and the literature [51, 63] and performed a simple validation by overlaying the location of existing water harvesting systems over the suitability maps.

### 3. Results

**3.1. Suitability for Water Harvesting Based on AND Boolean Analysis.** Using a Boolean MCE analysis, a large part of the Upper Blue Nile Basin was found to be suitable for both in situ and ex situ water harvesting systems (Figure 3). The suitability study of the in situ systems showed that water harvesting might be successfully implemented in the eastern and the northern part of the basin, while the ex situ systems could be applicable in most areas in the basin, in particular in the central and eastern part. Since slope was not considered as a determining factor for in situ water harvesting systems, areas considered suitable for in situ systems include land closely located to rivers, which actually comprise steep slopes. In situ systems in such areas could be implemented as soil conservation methods. However, in the ex situ systems' analysis, areas following the main Blue Nile and most of its tributaries were not classified as suitable for water harvesting, since areas with slopes greater than 8% were excluded from the analysis (Figure 3(b)). Areas in the west are dominated by woodland and bamboo forests, and as a result they were not found suitable for these agricultural interventions.

Of the total rainfed agricultural land, 50% was found suitable for in situ water harvesting systems and 36% for exsitu systems (Table 4). A combined analysis showed that 70% of the total rainfed agricultural land (a 16% overlap between the in situ and ex situ water harvesting suitable areas) or 36% of the total land is suitable for either of these systems.

**3.2. Suitability for Water Harvesting Based on Weighted Overlay Analysis.** The weighted overlay MCE analysis for

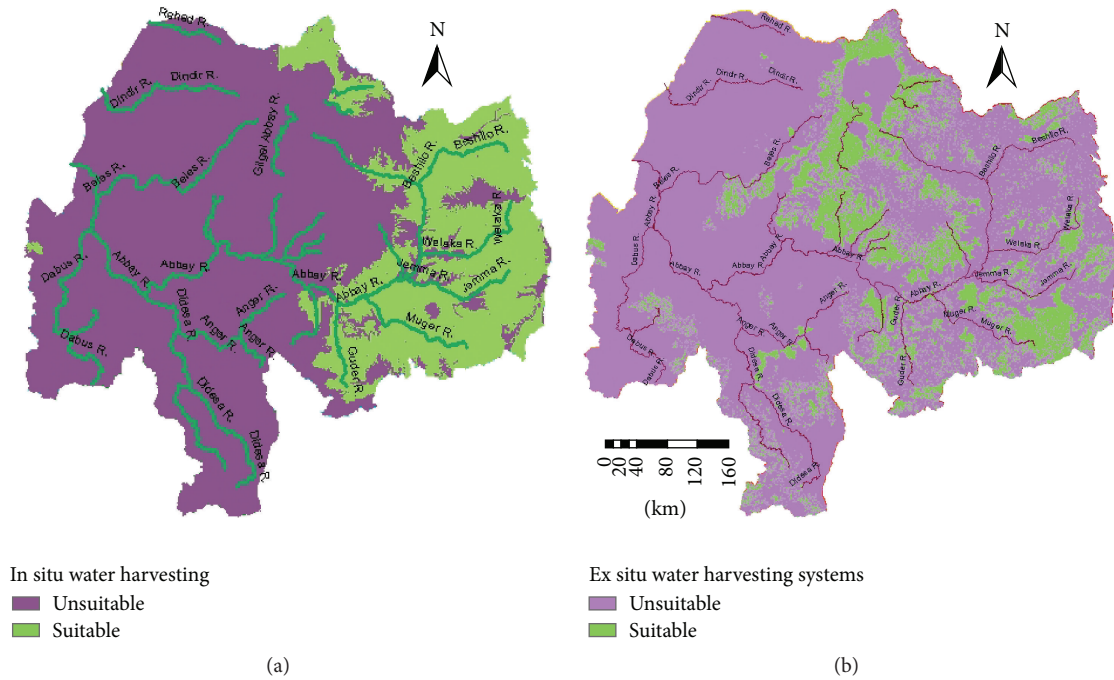


FIGURE 3: Suitability analysis for (a) in situ water harvesting practices and (b) ex situ water harvesting practices in the Upper Blue Nile Basin using a Boolean MCE technique.

TABLE 4: Suitability of the Upper Blue Nile Basin for water harvesting using a Boolean MCE technique.

RWH scheme	% suitable with respect to rainfed agricultural land	% suitability with respect to total land
In situ systems	50	26
Ex situ systems	36	19
Combined	70	36

equal percent influence for all determining factors showed that areas around Lake Tana region and the south-eastern part of the basin were classified as highly suitable for water harvesting (Figure 4(a)). The north-eastern and western parts of the basin were found to be moderately suitable for water harvesting. However, there are a number of smaller pockets of highly suitable areas for water harvesting in this part of the basin as well, while the central part of the basin was classified as having low suitability for water harvesting. None of the pixels in the study site reached either maximum (5) or minimum (1) suitability score (Table 5). In total, 24% of the basin was classified as highly suitable for water harvesting, 58% as moderately suitable, and 17% as less suitable using the equal weights condition. It was estimated that 2% of the basin was restricted land since water bodies, marshlands, and urban areas were excluded from the analysis (Figure 4(a)).

A higher influence factor assigned for rainfall and slope and, subsequently, a lower influence factor assigned for land cover and soil type reduce the extent of the most suitable area (Table 5, conditions 2 to 5). Areas in the central part

of the basin and along the Nile gorge which actually were highly suitable under condition 1 (Figure 4(a)) became only moderately suitable and less suitable in conditions 2 to 5 (Figures 4(b)–4(d)). This is attributed to the higher influence percentage applied to rainfall and slope. The most suitable area shrank significantly under conditions 3 and 5 (Table 5) which is because of the higher influence percentage assigned to the rainfall factor. These analyses indicated that rainfall is the biggest determining factor in estimating the suitability of water harvesting interventions in the basin.

The simple validation performed between the coordinates of existing water harvesting practices and our analysis showed good agreement (Figure 4); the existing water harvesting practices are located in the areas classified as most suitable and moderately suitable for water harvesting. Moreover, our results are consistent with studies done at country level by Mati et al. [40]. They stated that runoff water harvesting is potentially applicable throughout the country, while in situ water harvesting is applicable in most of the country. Using higher resolution data and taking different evaluation criteria, this study fine-tuned their work and thereby generated a spatially more explicit analysis for the Ethiopian Blue Nile Basin.

## 4. Discussion and Conclusion

**4.1. Ample Potential for Water Harvesting in the Upper Blue Nile Basin and a Need for Detailed Analysis at Mesoscale Catchment.** The suitability analysis carried out in this study has shown that the Upper Blue Nile Basin has a large potential for water harvesting. The area classified as most suitable

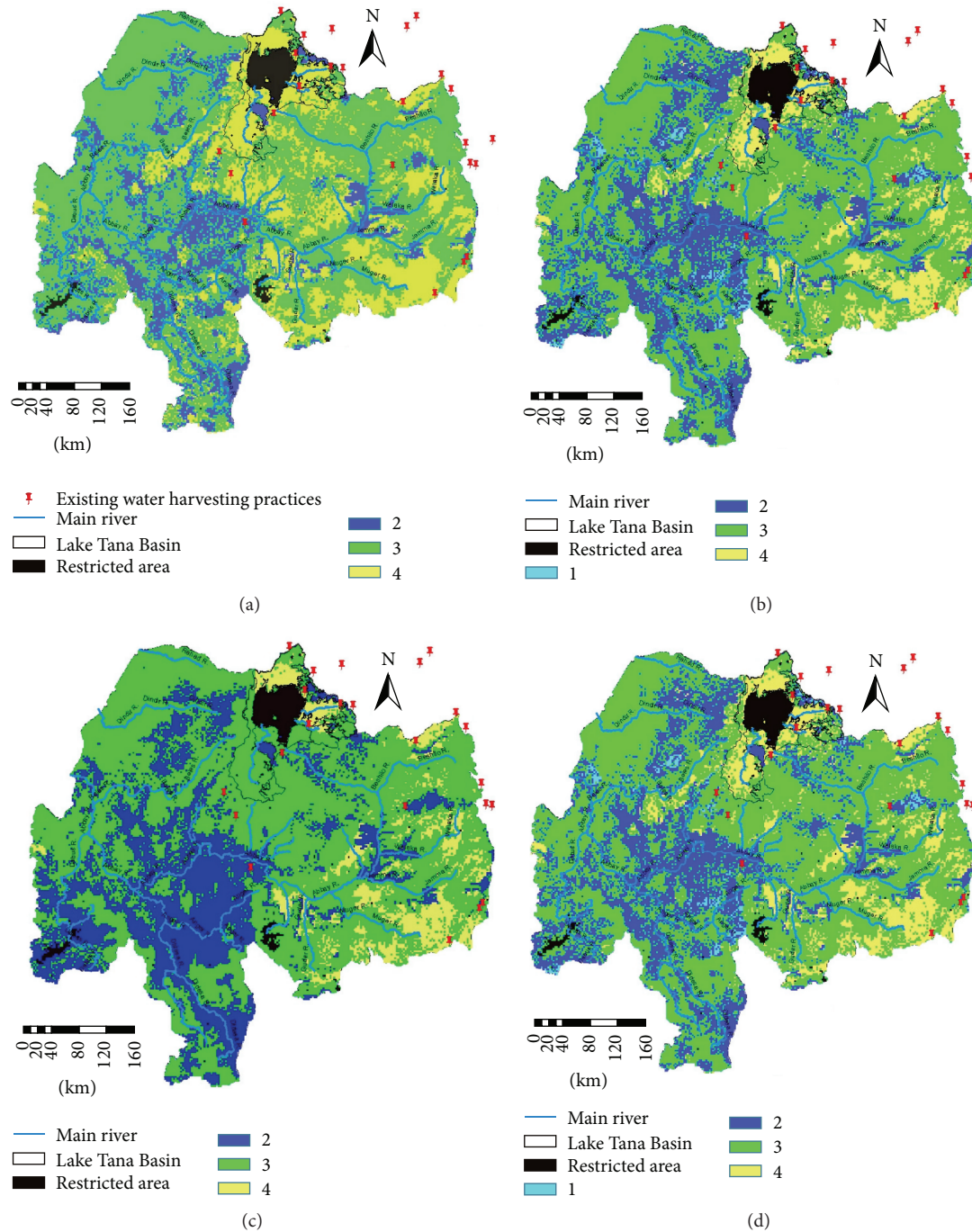


FIGURE 4: Suitability of the Upper Blue Nile Basin for water harvesting under: (a) equal percentage influence of factors considered; (b) percentage influence of 30, 30, 20, and 20 for rainfall, slope, land cover, and soil, respectively; (c) percentage influence of 35, 25, 20, and 20 for rainfall, slope, land cover, and soil, respectively; and (d) percentage influence of 25, 35, 20, and 20 for rainfall, slope, land cover, and soil, respectively (4: highly suitable, 3: moderately suitable, and 1-2: less suitable).

covers 6% to 24% of the land depending on how the weights of determining variables are assigned. Moreover, more than 50% of the study area was classified as moderately suitable. Areas considered suitable for water harvesting are located around Lake Tana in the north and in the eastern part of the study area. Most of these areas are spread in smaller

pockets at different parts of the basin, which in the case of water harvesting systems does not pose a problem since these schemes are implemented on a case-by-case basis. This study found that the results are highly sensitive to estimates of available rainfall. This means that changes in rainfall, which are predicted in the future due to anthropogenic climate



TABLE 5: The suitability levels for water harvesting of the total basin area (in percent) according to different weight combinations of influencing variables: suitability levels 1-2: low suitability, suitability level 3: moderate suitability, and suitability levels 4-5: high suitability.

Suitability level	Condition 1	Condition 2	Condition 3	Condition 4	Condition 5
5	0.00	0.00	0.00	0.00	0.00
4	23.68	11.92	8.26	10.15	6.49
3	57.72	61.41	61.21	62.99	61.55
2	16.43	23.50	28.34	23.71	29.75
1	0.00	0.97	0.00	0.97	0.00

Note: condition 1 is with equal weighting among all factors; condition 2 places highest weight on rainfall and slope; condition 3 has highest weight assigned to rainfall; condition 4 has highest weight assigned to slope; and condition 5 differentiates among all four factors, with rainfall being the most important.

change, might alter the results. With increasingly erratic rainfall the need to store water to bridge intraseasonal dry spells is likely to become more important in the study area.

The two applied methods showed consistent results. The areas identified as most suitable for water harvesting under the weighted overlay MCE were mostly located in the same areas identified as suitable for in situ and ex situ water harvesting in the Boolean MCE. The weighted overlay analysis enabled an assessment of the degree of suitability of the entire basin. This is, however, a less stringent suitability analysis, as it allows for compromise between suitability factors. For example, the AND Boolean analysis showed that areas in the west are unsuitable for in situ and ex situ water harvesting systems since this area includes woodland and bamboo land use types, but the weighted overlay analysis instead showed a moderate suitability. Even in the weighted MCE analysis these land use types were assigned a rather low suitability score. However, due to higher suitability scores from the other determining factors, these parts of the basin turned out to be classified as moderately suitable.

If nonagricultural land use types, such as open woodland (normally used for grazing), were given a higher suitability score in the analysis, the area classified as suitable for water harvesting would increase substantially. Investing in water harvesting on such land would possibly improve water availability for livestock, thereby potentially increasing farmers' income from livestock rearing. This may increase farmers' tendency to invest in agriculture, which has a synergetic effect on improving water productivity [1]. The water collected from nonagricultural land use types can also be transferred into agricultural fields for cultivation, even if the cost of relocating the water and land tenure issues demands a detailed assessment. Soil types in the open woodlands are commonly Luvisols, Cambisols, and Vertisols, which are very suitable for water harvesting for agriculture. On the other hand, the soil types in the cultivated fields are predominantly Leptosols, which are less suitable for agriculture and water harvesting practices. This suggests that there is an opportunity to transform woodland into agricultural land and gain a lot of benefit from water harvesting systems. The question, though, is whether ecosystem functions and services generated from woodlands can be maintained, for example, by adopting a spatial configuration of new agricultural land that maintains high levels of woodland biodiversity. For instance agroforestry is suggested as an option for sustainable agricultural intensification [16, 33, 64].

Water harvesting schemes can improve agricultural yield at field scale [24, 31]. However, the implication of upstream large scale implementations to downstream water availability and thereby the ability to meet social and ecological needs has not been investigated [1]. Such studies would require detailed mesoscale hydrological modeling. So far, though, catchment hydrology has had limited capacity to include small-scale water harvesting systems due, at least in part, to the lack of spatial suitability analyses of water harvesting potential. A key focus of future research should be on impact of large scale adoption of water harvesting at a catchment scale on upstream-downstream availability of water and social-ecological resilience.

Similarly, there is a need to develop methods and provide analyses on the role of water in building social and ecological resilience in catchments and river basins, using integrated approaches that consider synergies and tradeoffs between upstream and downstream water management interventions, for example, the choice between multiple water harvesting investments upstream and single dam developments downstream in river basins. From our initial suitability analysis it seems clear that Lake Tana river basin is an excellent region to advance such an integrated social-ecological water analysis, given the suitability for water harvesting, the high degree of planned large scale dams, the richness of the ecosystem functions and services provided by Lake Tana system, the risks facing this river basin from climate change, and, above all, the large development needs among poor rural communities. Future research needs to advance mesoscale hydrological analyses of the implications of various water resource management strategies and their implications for social-ecological resilience.

**4.2. Need for Considering Socioeconomic Factors for Suitability Analysis.** This study uses biophysical data to identify suitable areas for water harvesting implementation in the Upper Blue Nile Basin. Physical suitability analysis is the first step towards identifying suitable areas for water harvesting and helps to identify priority watersheds that can be used for further investigation of the implementation of water harvesting. Moreover, since physical suitability analysis uses input data, such as soil, land cover, slope, and rainfall, it is helpful to determine the type of water harvesting system (e.g., in situ or ex situ) that would be suitable under varying environmental conditions.

Once priority areas for water harvesting are identified through physical suitability analysis, other factors should also be included into the analysis to establish a fully successful water harvesting implementation. Various literature indicated that well-functioning market system, skilled human resources, socially viable technology, and stakeholder engagement [18, 26, 51, 65, 66] are among the main factors that determine the suitability of water harvesting implementation. Thus, performing socioeconomic analysis and stakeholder consultation are needed for a robust suitability water harvesting analysis.

Socioeconomic analysis such as cost-benefit analysis and comparative economic studies among different technologies should be conducted to get a better insight into selecting the most profitable technologies. Such an economic analysis should consider both short-term and long-term benefits. Some technologies, such as in situ water harvesting systems, have long-term benefits and their short-term benefits may not be easily visible. Access to markets, labour availability, resource endowment, such as wealth including land, and gender and education are among the key determinants of water harvesting implementation which require thorough consideration in the socioeconomic analysis (e.g., [67]). For example, Biazin et al. [65] suggest that the production of vegetables using water harvesting requires a market that is easily accessible, since the produce cannot be stored or transported easily. Boyd et al. [68] show how improved access to markets and increased producer prices stimulate investment in in situ water harvesting systems at the household level in Tanzania. Rămi [51] reports that ex situ water harvesting systems are labour-intensive. Munamati and Nyagumbo [67] show that resource status and gender issues were directly related to the performance of in situ water harvesting in the Gwanda district of Zimbabwe: wealthy and man-headed households performed better with in situ water harvesting systems. Boyd et al. [68] showed that farmers with some level of education performed better with in situ water harvesting systems than those with no education. Social values and settings also determine the uptake of water harvesting systems. For example, the Konso people in southern Ethiopia are known for constructing terracing systems. They can easily understand and implement different types of in situ water harvesting system. Some societies may be reluctant to use ex situ water harvesting systems, believing that such systems might increase the incidence of malaria, as well as the risk of drowning for children and animals [51]. Thus, socioeconomic analysis aids the design of water harvesting systems that fit the socioeconomic context of a given area.

Stakeholder consultation and an accompanying site visit can help to cross-check the feasibility of identified water harvesting systems through physical suitability to the local context. Moreover, consultations with beneficiaries, government agencies, and nongovernmental organizations help to identify specific challenges and opportunities that should be included in the design and planning of water harvesting implementation. For example, Rămi [51] reports that some farmers prefer water harvesting systems that require less human input in their construction and use. In regions where there is land scarcity, farmers are more interested in water

harvesting systems that take up less space. This dialogue with the stakeholders can be used to create awareness and thereby develop interest in implementing the technologies. It also creates avenues for capacity building on how to implement, use, and maintain the technologies. Engaging the stakeholders, particularly farmers, creates ownership of the projects, which increases the sense of responsibility for maintaining and taking care of the systems. This, in turn, increases the chances of success.

Physical suitability analysis, accompanied by socioeconomic analysis and stakeholder consultation will lead to a robust water harvesting suitability analysis. However, successful water harvesting implementation also demands proper planning, monitoring, and evaluation.

## Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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